88-Inch Cyclotron Operations

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The 88-Inch Cyclotron is operated as a national facility in support of U.S. Department of Energy programs in basic nuclear science. The central component is a sector-focused, variable-energy cyclotron that can be fed by either of two Electron Cyclotron Resonance (ECR) ion sources, the ECR and the AECR-U. This versatile combination produces heavy-ion beams of elements throughout the periodic table as well as high-intensity light ions, supporting forefront scientific research in nuclear structure, heavy elements, exotic nuclei, reaction mechanisms, nuclear astrophysics and weak interactions. The Cyclotron also provides beams for the application of nuclear techniques to other areas of research, including biology and medicine, atomic and high-energy physics. The Cyclotron is also used by industrial partners from aerospace and semiconductor corporations, NASA, DOE and DOD laboratories, and companies and laboratories from Europe and Japan. Both protons and heavy-ion beams simulate the cosmic-ray environment of space for radiation effects studies of microcircuits and other materials and for calibrations of detectors for future space probes.

Accelerator Use

FY98 was a time of transition for the 88-Inch Cyclotron. 3825 research hours (beam on target) were produced, down considerably from the record of 6243 hours in FY97. Several factors contributed to this decline, most notably the fact that the FY97 Summer Maintenance period was postponed until early FY98, in order to maximize the scientific opportunities with the Gammasphere detector prior to its move to Argonne National Laboratory. In addition, new facilities came on line in FY98: the 8-Pi Spectrometer was moved from Chalk River to take to place of Gammasphere in Cave 4C and began operation in April 1998. The Berkeley Gas-Filled Spectrometer (BGS) was installed in Cave 1 and commissioning runs began late in FY98, with production runs beginning in FY99. Efforts intensified on two fronts towards limited radioactive ion beams (RIB) efforts at the Cyclotron: Berkeley Experiments with Accelerated Radioactive Species (BEARS) is a project to couple the 88-Inch Cyclotron with the Biomedical Isotope Facility (BIF), a small proton cyclotron capable of producing light proton-rich radioactive ions. Test runs were performed throughout FY98 in this effort with the first physics runs taking place in early FY99. Also, a RIB test stand is under construction for initial experiments with ^{14}O. All four of these major new projects were manpower-intensive but did not require a lot of beam time in FY98. With the 8-Pi Spectrometer and BGS now in production mode, and BEARS reaching that plateau by summer, research hours are expected to be up in FY99. The Cyclotron will continue to operate on a 20 eight-hour shift/week schedule, with approximately 800 hours more research time than in FY98.

The Accelerator Operation Summary (Table 1) shows the breakdown of beamtime in FY98. A total of 204 users took part in experiments. There were 70 scientists and 35 students participating in 65 nuclear science experiments and they came from 9 universities, 2 DOE laboratories and 13 foreign institutions. 95 scientists and engineers and 4 students participated in non-nuclear science experiments from 24 institutions and companies. Their work included industrial applications with semiconductors and materials, calibration of detectors for the Advanced Composition Explorer (ACE) space probe, biology and medicine and the testing of detectors and electronics for the Atlas detector under construction for the Large Hadron Collider at CERN.

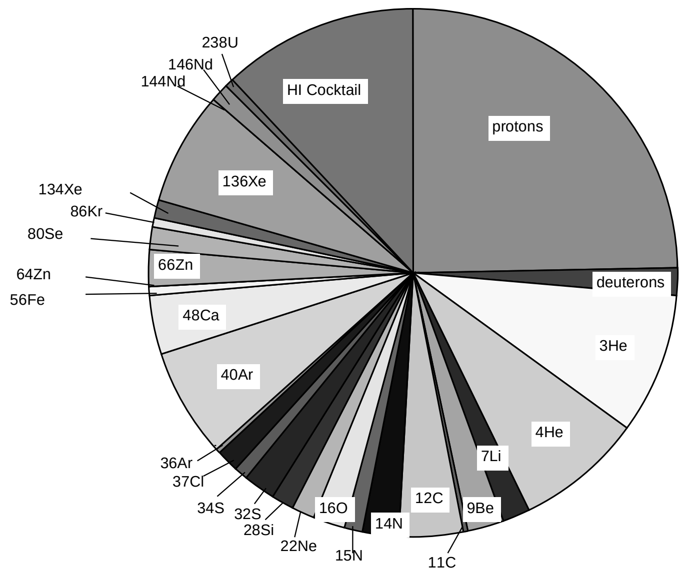
Ions, Energies and Intensities

The diverse research program at the facility dictates that the 88-Inch Cyclotron operate in many modes. For nuclear structure, a wide variety of heavy ion beams, including many rare isotopes, are required at modest intensities and energies. For the new BGS program, high-intensity medium-to-heavy mass ions are needed, many requiring new development efforts. Many of the other nuclear science programs, as well as biology and high-energy physics, require the use of light ions at high energies and a wide range of intensities. For the applied program, “cocktails”, or mixtures of beams are often used at low intensities and moderate-to-high energies. The versatility necessary to service all of these programs is demonstrated in Figure 1, a Chart of the Nuclides of 88-Inch Cyclotron beams. 45 different elements and 91 isotopic species have been accelerated at the Cyclotron. Some of the rare isotopes are run using enriched material, others using natural, depending on the intensity required. The color coding of the chart represent orders of magnitude in intensity for energies around the Coulomb barrier (≈5 MeV/nucleon), a typical energy for both nuclear structure and BGS runs. These intensities are based on actual runs; in many cases, a species has never been tuned for maximum intensity. It is expected that many of these intensities will increase as new beams are developed for BGS experiments.

Figure 2 shows the beams actually run at the 88-Inch in FY98. Almost 47% of the beam time used light ions ($Z \leq 4$), an increase of 17% which reflects the changes in the Cyclotron program with the loss of the Gammasphere detector. A wide variety of heavy ions were run as well, including the new beams ^{144,146}Nd (out of natural) and ^{80}Se, both for nuclear structure experiments. In FY97, 13% of the beam time went to running the rare isotopes ^{36}S and ^{48}Ca, popular beams for neutron-rich nuclear structure studies using Gammasphere. This percentage dropped to 4% in FY98, partly due to the overall drop in nuclear structure running with the 8-Pi Spectrometer operational only half the year, and partly due to a shift in emphasis of the approved nuclear structure experiments using the less sensitive 8-Pi Spectrometer.

In FY99 the 88-Inch Operations group will continue to develop high-intensity beams for use with the BGS detector. Completion of the detector provides an opportunity to search for superheavy elements at the Cyclotron. Two of the most promising reactions will require the use of high-intensity ^{48}Ca beams for several week periods. The separated isotope ^{48}Ca is very costly and in short supply, so the Operations group is presently evaluating the best methods to increase the efficiency of ^{48}Ca production in the AECR-U to provide these beams.

Figure 2. FY98 Beams



ECR Ion Source Development

A new very high-magnetic field superconducting ECR ion source, the Third Generation ECR, is under development. It will boost the maximum energies and intensities for heavy ions from the cyclotron particularly for ions with mass 160 and above. Recent progress on ECR ion sources indicates that significantly higher performance can be obtained by incorporating very strong magnetic fields to improve the plasma confinement and by using multiple frequency heating to enhance electron heating. The plasma chamber will be made from aluminum to provide additional cold electrons, three separate microwave feeds to allow multiple-frequency plasma heating (at 10, 14 and 18 GHz) and very high magnetic mirror fields. The magnetic fields in the source will be at 4 Tesla at injection and 3 Tesla at extraction and have a radial field strength at the wall of 2.4 Tesla.

Phase I of the AIP project is focused on construction of superconducting solenoids and sextupole magnets and test operation in a vertical dewar. The solenoid was completed during the summer and successfully cold tested, reaching its full design field without quenching. The sextupole coil is currently being wound and will be tested this spring. Phase II includes the construction of the horizontal cryostat, helium batch fill system, and iron yoke for the magnet and tests to verify that the system meets the required cryogenic and magnetic field specifications. The full project is expected to be completed during FY2001.

Radioactive Beam Technology

The 88” Operations group is collaborating on two projects which involve the production, transportation and ionization of radioactive atoms. This is both important for development of new scientific opportunities at the Cyclotron and to further the technologies critical for future radioactive beam facilities such as the ISOL currently being discussed.

BEARS has shown that ^{11}C, with a 20 min half life, can be ionized in the AECR-U and accelerated through the Cyclotron into an experimental area with an overall efficiency of about 1%. With the initial batch tests, peak efficiencies of 1 x 10^8 were achieved. One issue still to be addressed is whether the Cyclotron can perform better mass separation of a radioactive beam from its contaminants. For ^{11}C, for example, the contaminant beam is ^{11}B. ^{11}B appears to linger in the source for a long time after it is used as a beam. It is also present in small quantities from boron-containing ion source parts and also builds up during the course of a BEARS run from the decay of the ^{11}C in the source. For experiments at higher energies ($\geq$ 6 MeV/nucleon), the $^{11}C/^{11}B$ can be separated using a stripper foil to strip the carbon from +4 $\rightarrow$ +6 with 99% efficiency. At lower energies, the stripping probability goes down and separation by stripping becomes inefficient, so other means need to be explored, namely whether there are ways to tune the Cyclotron in order to improve its frequency resolution and thus its mass resolution.

The goal of the second RIB project, the ^{14}O experiment, is to produce this short-lived (70 sec) isotope using the Cyclotron, and to transport it through a vacuum line as CO to an ion source, where it will be ionized and accelerated to 30 kV and then implanted to provide an ^{14}O source for beta shape spectrum measurements. An exotic beam test stands was constructed for this purpose in FY98 and then used to test a RF multicusp source provided by the Ion Beam Technology group of the Accelerator and Fusion Research Division at LBNL. These tests using calibrated gas sources indicated that the efficiency of this source was less than 1% for CO and that the antenna lifetime was too short for this application. The multicusp source has been replaced by an ECR ion source, IRIS, which is currently being installed on the test stand and will be in operation in early spring. During FY98, a high temperature carbon target was developed and tests demonstrated efficient release of the ^{14}O in the form of CO and transport to the exotic beam test stand.

During FY98, measurements were made on the AECR-U source which demonstrated unexpectedly high ionization efficiencies using calibrated gas leaks. Measured efficiencies and hold-up times are shown in Table II. Ionization efficiencies as high as 33% were measured for O^{6+} using a CO_2 leak, with a total efficiency for ionization into charge states +5, +6, and +7 of greater than 50%. The carbon efficiencies from the same calibrated leak show almost 40% ionization efficiency into charge states +4 and +5. These large efficiencies suggest that ECR sources may be a viable alternative to the charge state stripping being proposed for ISOL designs.

Table 1
Accelerator Operations Summary – FY98

Accelerator Operation Summary (hours)	
Research	3825
Tuning	723
Machine Studies	254
Unscheduled Shutdowns	188
Scheduled Shutdowns	3770
Electrical Energy Consumption (GWH)	4.4
Cost of Electrical Energy (Thousands of Dollars)	319
Financial Support for Accelerator Facility	
Operation (Thousands of Dollars)	
Heavy Ion Physics (KB-02-02)	3715
Biomedical and Environmental Research	0
Other Sources	519
Total	4234
Experiment Summary	
Beam Utilization for Research (Hours)	
Nuclear Research	2680
Atomic Physics	53
Biology and Medicine	122
High Energy Physics	320
Applied Research (recharge)	650
Total	3825
Nuclear Science Research	
Number of Nuclear Science Experiments	65
Number of Scientists Participating	70
Number of Students	35
Institutions Represented	
Universities	9
DOE National Laboratories	2
Foreign Institutions	13
Other government labs	0
Non-nuclear Science Research	
Number of scientists and engineers	95
Number of students	4
Institutions and Companies	24
Total users (all research)	204
Percentage of Beam Time (all research)	
In-House Staff	32%
Universities	29%
DOE/Government Laboratories	0%
Industry	20%
Foreign Institutions	19%

Table II. Ionization efficiencies and hold up times for selected charge states of oxygen, carbon and fluorine ions produced by the LBNL AECR-U ion source with CO, CO_2, O_2 and CHF_3 calibrated leaks.

CO	(%)	τ_{fast} (sec)	*CO_2*	(%)	τ_{fast} (sec)	*O_2*	(%)	τ_{fast} (sec)	*CHF_3*	(%)	τ_{fast} (se
O^{5+}	11.5	3.2	O^{5+}	12.5		O^{2+}	3.9		F^{5+}	2.8	
O^{6+}	26.3	3.2	O^{6+}	33	7.1	O^{3+}	8		F^{7+}	4.5*	4.5
O^{7+}	7.5	3.2	O^{7+}	7.44		O^{5+}	11.3		F^{9+}	0.7*	
						O^{6+}	16.0	4.7			
C^{4+}	23.7	2.9	C^{4+}	23.4	5.6	O^{7+}	5.6		C^{4+}	18	4.3
C^{5+}	14.1	2.9	C^{5+}	15.4							

* using 8x8 mm resolving slits

88" Cyclotron Beam